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Monolithic fiber-top sensor for critical environments and standard applications

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We present a monolithic device obtained by carving a cantilever on the top of a single-mode optical fiber. We show that the vertical position of the cantilever can be determined with accuracy comparable to atomic force microscopes and other commonly used scientific instruments. The device does not require any alignment procedure and can be used in critical environments as well as in standard applications. © 2006 American Institute of Physics. [DOI: 10.1063/1.2170139]

Micromachined cantilevers are the most elementary and successful example of miniaturized sensors. A free-standing rectangular beam can often detect changes in the chemical, biological, and physical properties of the surroundings with sensitivity comparable, if not superior, to much more complicated devices. It is thus not surprising that this simple design is still at the heart of several scientific instruments, the most celebrated of which is the atomic force microscope (AFM).¹ These instruments rely on the possibility to measure the vertical position of the suspended edge of the beam with atomic accuracy, a level of precision that can be achieved by electronic readout (e.g., tunneling probes,¹ integrated field-effect transistors,² capacitive methods,³ piezoelectric or piezoresistive devices)^{4,5} or with optical techniques (e.g., optical levers^{6,7} or optical fiber interferometers⁸⁻¹⁰). Electronic readouts are not always compatible with the environment where measurements must be performed (e.g., electrically conductive liquids or extreme temperatures). Furthermore, their fabrication often involves rather cumbersome and expensive processes, an important detail that has limited their commercial and scientific impact. Optical techniques are much more widespread, as, in principle, they do not offer any real limitation. However, they generally require an inconvenient alignment procedure, which can also represent a major technical challenge for applications beyond standard experiments.

In this letter we present a *plug-and-play* device suitable for AFM measurements in critical environments and other applications where cantilevers can be used. The device is obtained by machining a thin rectangular beam out of the cleaved edge of an optical fiber (see Fig. 1). The vertical displacement of the cantilever is determined by measuring the interference of laser light reflected at the fiber-to-air edge with that reflected by the cantilever, as in common fiber interferometers. Because of its monolithic structure, the device does not require any alignment procedure. The displacement sensitivity is comparable to commercially available AFMs,

suggesting that *fiber-top* cantilevers might represent an interesting alternative not only for critical environments, but also in standard experiments.

In Fig. 1 we show a scanning-electron-microscope image of the device. A single-mode optical fiber (core diameter = 9 μm , cladding diameter = 125 μm) was stripped of its jacket, cleaved, and coated with a thin metallic layer (5 nm Cr, 20 nm Pd) to prevent electrostatic charge accumulation in the next fabrication step. The metal coated edge of the fiber was micromachined by means of a focused-ion beam technology to obtain a cantilever anchored to the fiber, parallel to its edge, with its center point suspended over the core of the fiber. The fiber was then placed vertically inside a thermal evaporator, where a ≈ 100 nm silver coating was deposited.

The device was plugged to the readout instrumentation sketched in Fig. 2. The light of a laser beam (1.31 μm wavelength), coupled to the fiber, is partially reflected at the fiber-to-air, air-to-cantilever, and cantilever-to-metal interfaces back into the fiber. While propagating backwards, the three signals enter a fiber coupler that transmits $\approx 50\%$ of the optical power to another fiber aligned with an infrared sensor. If multiple reflections are neglected, the output signal of the detector is given by

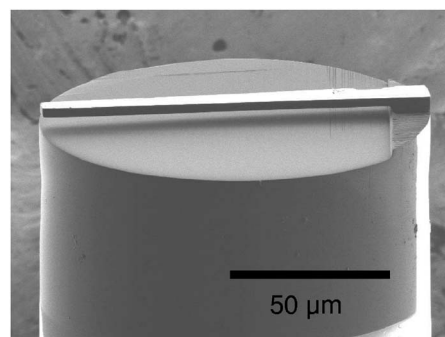


FIG. 1. A scanning-electron-microscopy image of the fiber-top cantilever (before the evaporation of the silver layer). Dimensions: length ≈ 112 μm , width ≈ 14 μm , thickness ≈ 3.7 μm .

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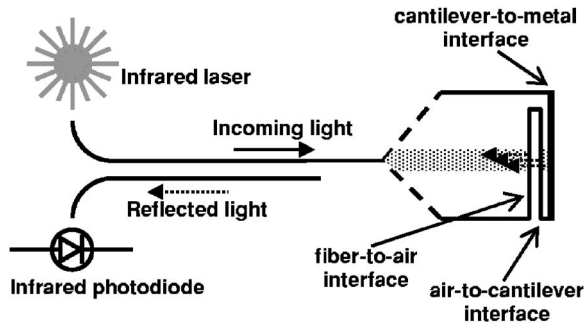


FIG. 2. Schematic view of the readout technique. The continuous arrow represents the input light. Dashed arrows represent the light reflected at the fiber-to-air, air-to-cantilever, and cantilever-to-metal interfaces. The shaded area represents the core of the fiber (diameter=9 μm) (not to scale).

$$W = W_1 + W_2 + W_3 - 2\sqrt{W_1 W_2} \cos \frac{4\pi d}{\lambda} - 2\sqrt{W_1 W_3} \cos \left(\frac{4\pi d}{\lambda} + \frac{4\pi n t}{\lambda} \right) + 2\sqrt{W_2 W_3} \cos \frac{4\pi n t}{\lambda}, \quad (1)$$

where W_1, W_2 , and W_3 are proportional to the amount of light reflected at the fiber-to-air, air-to-cantilever, and cantilever-to-metal interfaces, respectively, d is the separation between the edge of the fiber and the inner surface of the cantilever, t is the thickness of the cantilever, n is the refractive index of the core of the fiber, and λ is the wavelength of the laser. Equation (1) can be written as

$$W = W_0 \left[1 - V \cos \left(\frac{4\pi d}{\lambda} + \phi \right) \right], \quad (2)$$

where ϕ is a constant, V is the fringe visibility, and W_0 is the midpoint output. V and W_0 are related to the output signals corresponding to maximum (W_{\max}) and minimum (W_{\min}) interference according to

$$V = \frac{W_{\max} - W_{\min}}{W_{\max} + W_{\min}}, \quad (3)$$

$$W_0 = \frac{W_{\max} + W_{\min}}{2}. \quad (4)$$

The displacement sensitivity close to quadrature is thus given by

$$\Delta d \approx \frac{\lambda}{4\pi} \frac{\Delta W}{W_0 V}, \quad (5)$$

where ΔW is the minimum detectable signal.

In Fig. 3 we show the readout signal obtained while touching the cantilever with a tip. Roughly 800 ms after starting data acquisition, the cantilever was brought to contact with the edge of the fiber. The first spike in the trace corresponds to the approaching movement. The cantilever was then left in contact position for ≈ 500 ms, as indicated by the flat part of the signal between the two spikes. Finally, the tip was retracted (second spike of the trace), allowing the cantilever to go back to its initial position (flat signal after 1.5 s). This experiment demonstrates that the device can be used as a position sensor.

To determine the displacement sensitivity, we have anchored the micromachined fiber to a hot plate. In Fig. 4 we

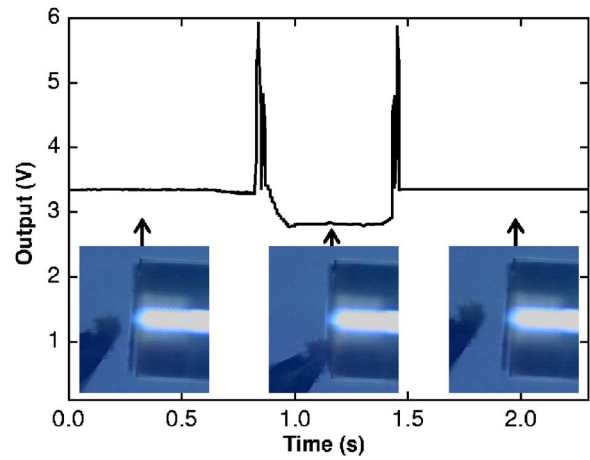


FIG. 3. (Color online) Readout output signal obtained in correspondence of a mechanical deformation of the cantilever. Images were obtained with an optical microscope and represents the different positions in which the cantilever has been set: (i) freely suspended (before contact), (ii) in contact with the edge of the optical fiber, and (iii) freely suspended (after contact).

plot the output signal as a function of the temperature of the hot plate. As the temperature increases, the stress induced by dissimilar thermal expansion of the metallic coating and of the optical fiber glass makes the cantilever bend. From the data reported, it is clear that during this deformation the output signal passes through an interference minimum and maximum [as expected from Eq. (2)]. According to our results, $W_{\min} \approx 3.1$ V and $W_{\max} \approx 4.8$ V. The rms noise of the output signal, measured with a digital oscilloscope in the whole available bandwidth (dc-400 MHz) over a 0.2 s time interval, is ≈ 3.5 mV, which corresponds to a vertical displacement of the cantilever of ≈ 4 Å.^{11,12}

The performances of our device are comparable with those of commercially available AFMs. The huge advantage of our system with respect to existing readout techniques is that it does not require any mechanical alignment. Our system is thus particularly suitable for measurements in critical environments, where other readout techniques could require less straightforward solutions. Applications beyond AFM experiments are also feasible. Fiber-top cantilevers could serve, for example, as accelerometers, vibrometers, temperature gauges, or gas and chemical sensors.

Apart from immediate applications, our device can be

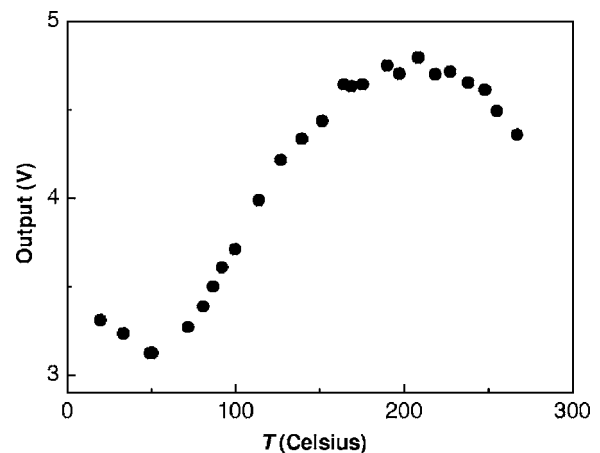


FIG. 4. Readout output signal as a function of the temperature of the cantilever.

considered a *proof-of-concept* of a more general alternative to commonly used micromachined designs. It is reasonable to envision that in a near future other fiber-top sensors will be developed for both scientific experiments and technological applications.

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¹¹The dominant part of the noise is associated to a high frequency periodic signal generated by the electronic readout and not by the fiber itself. The rms noise value does not change if a standard cleaved optical fiber is plugged to the readout system.

¹²According to calculations, the spring constant of our cantilever is roughly equal to 10 N/m. This value can be largely varied by changing the dimensions of the cantilever.